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AN INVESTIGATION INTO THE FEASIBILITY OF A PYROTECHNIC LASER PUMP

BY

CHESTER L. SMITH

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PICATINNY ARSENAL

DOVER, NEW JERSEY

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Approved by:

S. SAGE
Chief, Pyrotechnics Laboratory

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I INTRODUCTION

A. Objectives

In accordance with the decision of the Special Group on Optical Lasers (SGOOM), research responsibility for pyrotechnic-chemical pumping of lasers was assigned to Picatinny Arsenal, and funding for FY 63-64 has been provided by AMC direction (AMCMS Nos. 5563.12.41330 and 510.11.142). It was also directed that the larger part of this program be given to the Pyrotechnics Laboratory as mission and experience indicates.

The initial objectives of the Pyrotechnics Laboratory Laser Program were established as follows:

1. Determine pump requirements of solid state laser media.

2. Determine to what extent presently existing pyrotechnic and other sources meet these requirements.

3. Initiate development of items and systems to produce an effective means of pumping.

4. To demonstrate feasibility of pumping with relatively small pyrotechnic items.

B. Background

In considering various types of solid state lasers, it was decided first to concentrate on some of the common materials that could be operated at

ambient temperatures, that had the capability of the greatest power output, and also to consider some of the new higher sensitivity rods for use in demonstrations. The three types of rods chosen were the ruby, neodymium doped glass, and neodymium doped calcium tungstate.

In the initial part of the program it was decided to experiment with extremely small pyrotechnic items as a convenience in making measurements and handling. It was also considered important that items having a relatively low brisance (low explosive force), be experimented with.

Pyrotechnics have long been used as high intensity sources of light. These include flares, flash cartridges, flash bulbs, tracers, spotting charges, etc. Different classes of sources have long been known for their high efficiencies in light output per gram, as compared to conventional electrical sources, arc lamps, etc. Chemical sources of this nature have the advantage of being capable of presenting extremely large area surfaces and yet embody simple methods of initiation. Relatively bright sources have been produced from an item containing on the order of 200 or 300 milligrams of composition, and having a volume of 1/16 of a cubic inch. High flame temperatures can be attained with various compositions and metals, and combinations can be investigated that would give a strong discreet emission; that is, have strong lines in the particular absorption band of the desired medium. Although some theoretical work has been done, the mechanism for producing these temperatures by these compositions is not well

known. Higher temperatures can be expected when the reactions occur at higher pressures.

C. Initial Phases

Preliminary studies indicate the basic requirements for stimulation of the dopants in a transparent medium as:

1. Brightness temperature of the source
2. Source output wave length distribution
3. Rise time and duration of the brightness

As a starting point it was decided to investigate existing items such as squibs, detonators, flash cartiridges, etc. before any development on new vehicles was initiated. It was also decided to obtain brightness data on conventional sources for comparison to the chemical systems. Since very little information on these sources was found in the literature, it was necessary to perform these experiments also. Brightness measurements were taken on flash bulbs, xenon lamps, exploding wires, and used as a comparison to chemical sources.

It was also apparent that the radiant intensity of any pumping source would not necessarily be fully coupled to a laser rod so plans were made to measure the degree of coupling in certain pumping configurations.

Another phase was established as a study of compositions in an attempt to attain improved brightness. The approach was to optimize fuels and oxidants and investigate confinement, configuration, and methods

of initiation. It was also decided to engineer means of coupling the chemical pump to the laser through the design of new items with compatible configurations. The last phase planned was a demonstration of the feasibility of engineering hardware and items for pumping conventional laser rods.

II RESULTS

The listing of Table I represents the variety of compositions that were examined for brightness. These items ranged from pyrotechnic compositions in squib bodies to highly explosive photoflash cartridges. The investigation of these materials was a preliminary measure with intent of "weeding out" those compositions that do not look promising, and to obtain a relatively bright source with which to do detailed work. High explosives (such as PETN) and mixtures of explosives with pyrotechnic compositions produced brightness temperatures only slightly higher than some pyrotechnic compositions (Table II.) For instance, the brightness temperature of PETN/Barium Nitrate (78/22) produced a brightness of 4300° K, while a squib of $Zr/KClO_4$ burning with moderate confinement produced over 4000° K. The brisance of the explosives is high, however, and would pose a severe problem when trying to avoid damage of a laser crystal. Consequently, it was decided to work intensively with a pyrotechnic composition in a standard squib body rather than with an explosive. Furthermore, it was evident that the brightness of a squib device could be increased with confinement techniques, but the brightness of an explosive cannot be so enhanced. It was decided to use $Zr/KClO_4$ as one of the brightest representatives of the pyrotechnic compositions, and to concentrate on what ultimate brightness could be achieved with this composition. The squib body that was used was loaded with 120 mg of $Zr/KClO_4$ blended

TABLE I

LIST OF COMPOSITIONS & ITEMS TESTED

1. Flash Bulbs and Lamps

   a. #5 Flash Bulb
   b. AG-1 Flash Bulb
   c. E.G.G. FX100 Xenon Lamp
   d. Spiral Xenon Photo Speed Lamp

2. Explosive Compositions (Standard)

   a. M48 Detonator (PETN)
   b. M36 Detonator (PETN)
   c. 1E15 AEC Detonator (PETN)

3. Squibs (Standard)

   a. M1A1 Squib
   b. M2 Squib

4. Experimental Pyrotechnic Items, Mixtures, Compositions

   a. Titanium Potassium Perchlorate ($Ti/KClO_4$)

      (1) Nygon Tubing - Pyrocore - X311
      (2) M112 Fuse Body - Azide Relay

   b. Type III, Class A Photoflash Composition

      (1) Nygon Tubing - Pyrocore - X311
      (2) X311 Blasting Cap Loaded with Type III (1" Body, 1 3/8" Body)
      (3) XM66E2 Bodies Loaded with Type III (M-36 Body) Azide Relay
      (4) XM66E2 Body - Type III No Azide Relay
      (5) M112 Fuse Body - Type III, Azide Relay, Squib Ignition

c. Pyrotechnic - Explosive Systems (Detonator Type Items)

(1) Metal/PETN

(a) Ca/PETN Calcium
(b) Al/PETN Aluminum
(c) Zr/PETN Zirconium

(2) PETN/Oxidizer

(a)	PETN/Ba $(NO_3)_2$	Barium Nitrate
(b)	PETN/$NaNO_3$	Sodium Nitrate
(c)	PETN/$NaClO_4$	Sodium Perchlorate

(3) PETN/Photoflash Comp.

(a) PETN/Type III Class A

(4) Photoflash Composition - Azide Relay or X311 Initiator

(a)	Type III Class A	Al/Ba $(NO_3)_2/KClO_4$	40/30/30
(b)	FP907	Al/Ba$(NO_3)_2/KClO_4$	30/50/20

d. Pyrotechnic - Non-explosive Systems (Squib Type)

(1)	S198 Composition	$Zr/KClO_4/MoO_3$	(Non Stoichiometric
(2)	Zr/BaO_2 Mix	35/65	Stoichiometric
(3)	$Zr/KClO_4$	57/43	Stoichiometric
(4)	$Zr/KClO_4$	72/28	High efficiency systems

TABLE II

BRIGHTNESS TEMPERATURE DATA

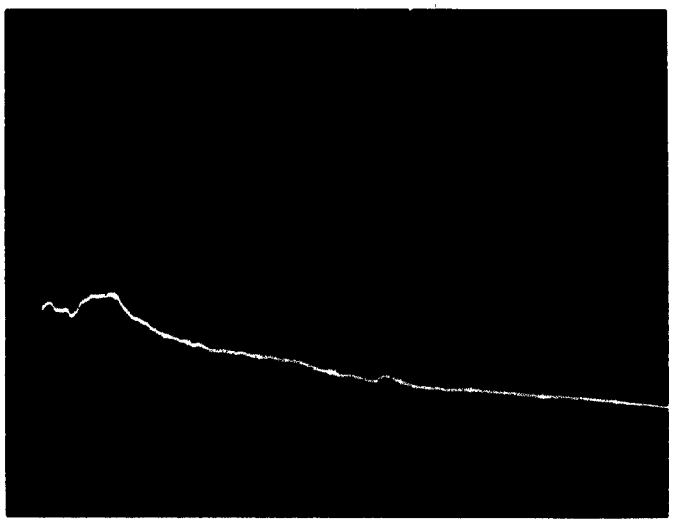
Composition	Brightness Temperature °K
PETN/Barium Nitrate (78/22)	4300
PETN Control	4000
Flash Bulbs, commercial	3800
Zirconium/Potassium Perchlorate (57/43) unconfined	3700
Zirconium/Potassium Perchlorate (57/43) confined	4800 - 5000
Xenon Lamp XF 100 (20 μf, 1400 volts)	8000
M-48 (Fired into conical hole)	7000
Laser Activating Grid (Zirconium/Potassium Perchlorate (57/43) 400 mg.	4200

in stoichiometric ratio. The composition was ignited directly from the bridge wire which was used without an initiating charge.

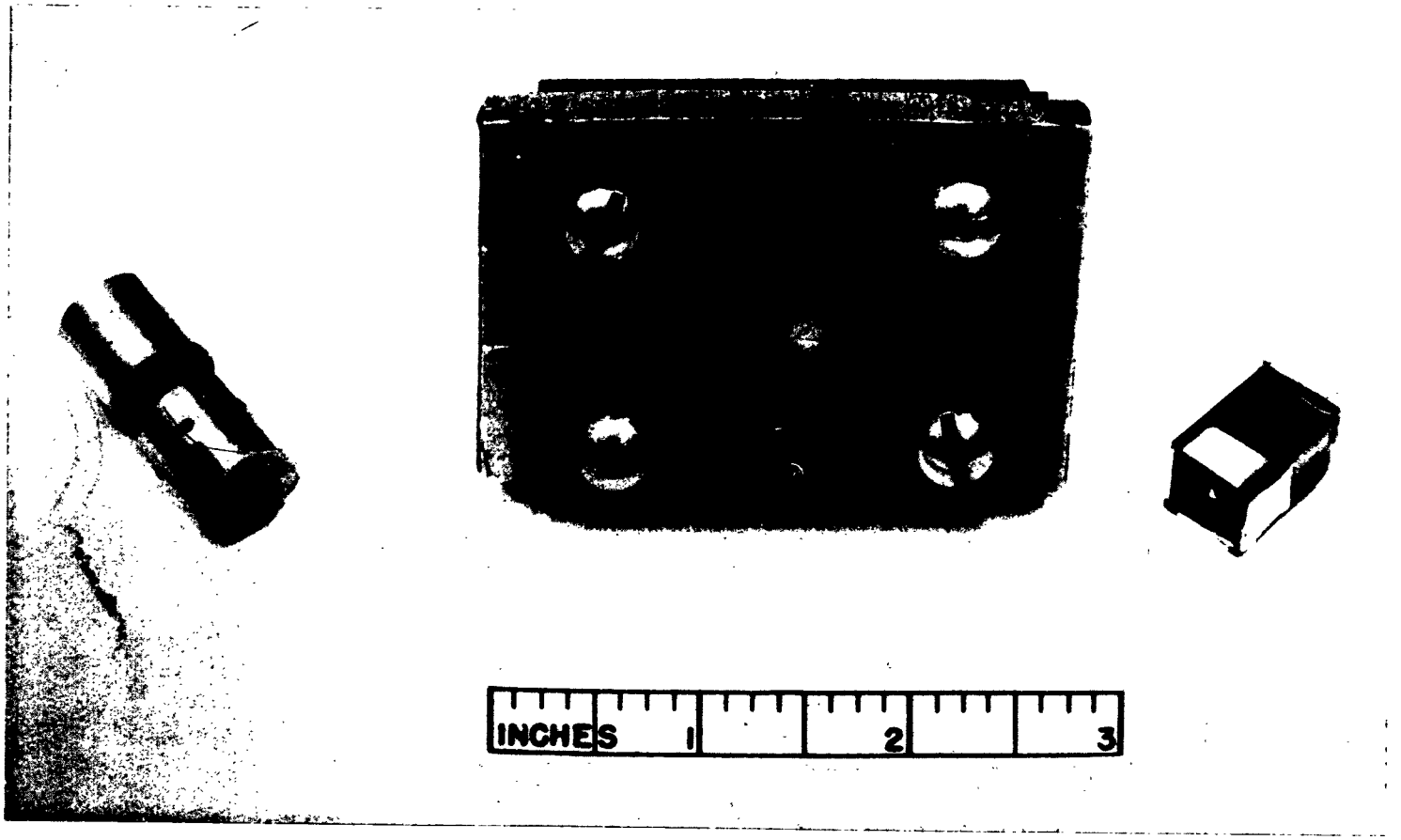
A. Effects of Confinements on Brightness

The brightness of the squibs was first measured. The squibs were unmodified and were used directly as they were received. Under these conditions, the brightness was approximately 3700° K at the peak point. Such a typical measurement is shown in Oscillogram 1. It was expected that if the squib were not allowed to blow out its composition, but was confined while it burned, the brightness might be higher. The squibs were confined by placing the squib body tightly into a hole in steel. A 1/4" sheet of lucite was placed over the squib to confine the gases and to act as a window. The brightness under these conditions immediately went up to an average of over 4000° K. Improvements were made in the confining fixture by using a neoprene gasket between the steel plate and the lucite, and also in the rear of the plate to prevent back flow of the gases. The fixture shown in Photograph 1 (center) gave the maximum brightness that was measured. This brightness is about 4900° K and an example of such a waveform is shown in Oscillogram 2. Attempts to confine still further have produced no additional brightness. In a fixture shown in Photograph 1 (left), the squib was completely confined and potted in steel with no venting. Under these conditions, the deflagration process inherent in a squib turned into a detonation process. This detonation then breaks through and destroys the fixture. Furthermore, when

Oscillogram 1 - $Zr/KCLO_4$ Squib Brightness (Unconfined)
.2 mses/cm



Oscillogram 2 - $Zr/KCLO_4$ Squib Brightness (Confined)
.2 msec/cm

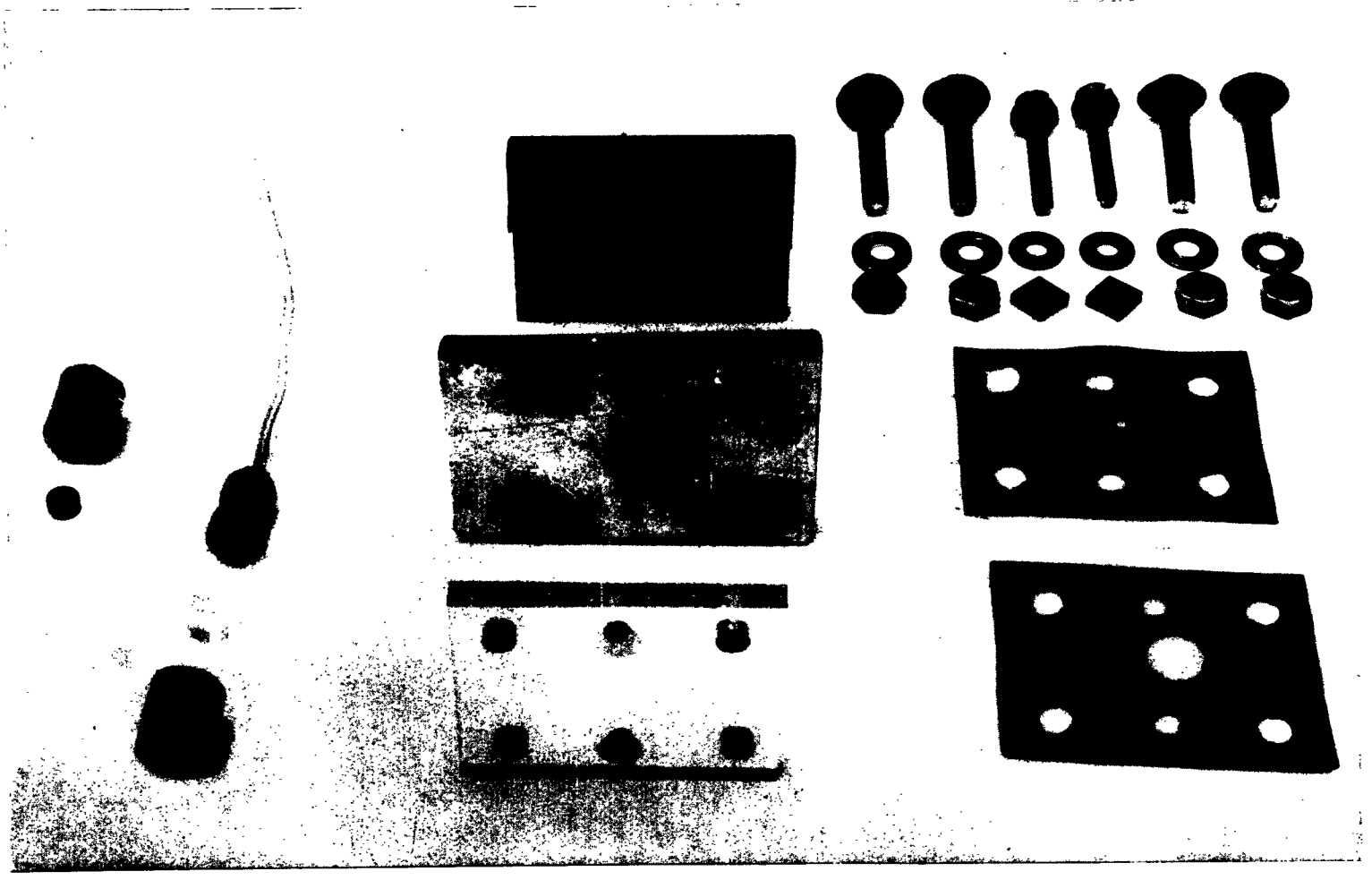


PHOTOGRAPH 1 - CENTER - Squib Confining Fixture
LEFT - Squib Confining Fixture (High Confinement)

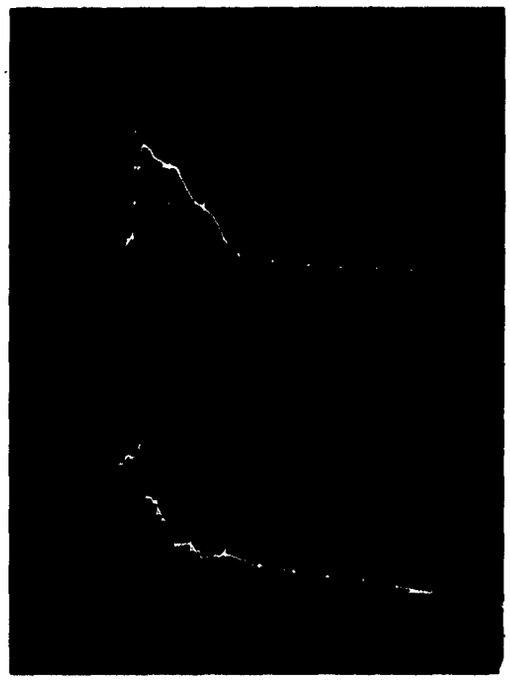
the highly confining fixture is used, the brightness appears very low ($< 4000^{o}K$). It is felt that with this higher confinement, the oxidation products of the reaction build up on the lucite window, rendering it nearly opaque. When the center fixture of Photograph 2 is used, the gasketing ruptures allowing the gases to flow radially outward between the lucite and the plate. This "flow" process keeps the lucite clear and allows a window into the center of the burning process. Photograph 2 shows exploded views of these fixtures. Oscillogram 3 shows two examples of squib brightness in the confining fixture.

B. Brightness of Distributed Pyrotechnics

A fixture has been designed to attempt to attain a continuous distribution of light and to attain the necessary simultaneity. A printed circuit (Photograph 3) contains a matrix of bridge wires with 44 bridge wires per square inch. The composition is poured over and pressed onto this bridge matrix with a sheet of lucite. A gasket is placed between the lucite and the printed circuit matrix. The entire "sandwich" is then bolted together. The purpose of the bridge matrix is to attempt to improve simultaneity of burning by multiple ignition of the composition. The resultant flame should then be a continuous distribution and will burn under confinement. A brightness measurement taken on the center of the burning area showed a peak of 4200^{o} K. Since this was a first attempt, this fixture can be improved upon, and higher brightnesses could probably be attained.

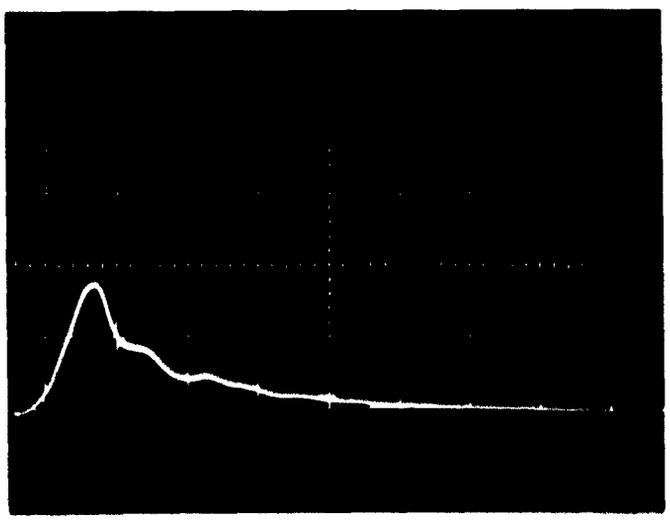


PHOTOGRAPH 2 - CENTER & LEFT - Squib Confining Fixture (Exploded View)
RIGHT - High Confinement Fixture (Exploded View)

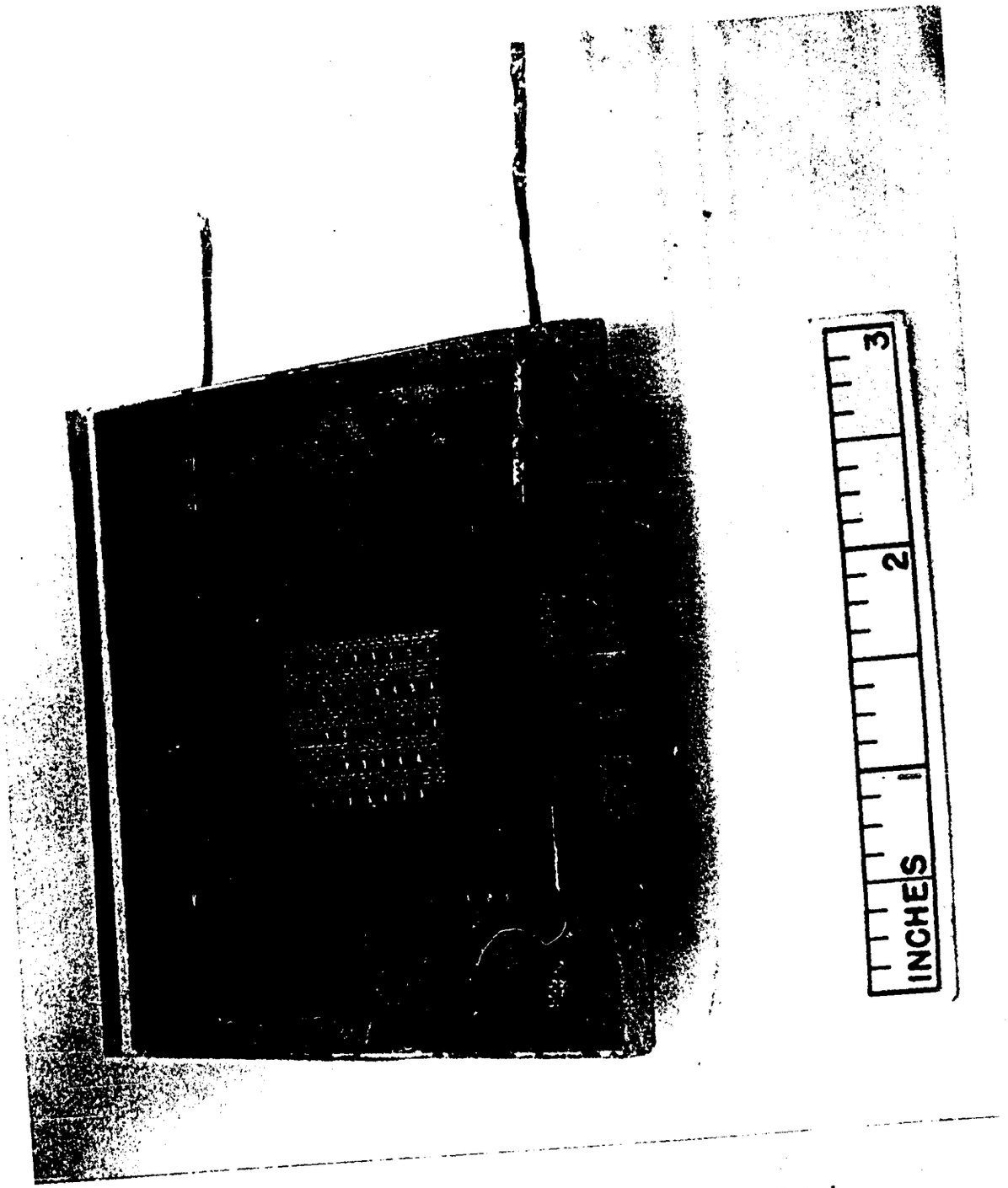


Oscillogram 3 - $Zr/KC10_4$ Squib Brightness (Confined)

.2 msec/cm



Oscillogram 4 - FX100 Xenon Tube Brightness (1400 V, 204 f)
10 msec/cm



PHOTOGRAPH 3 - Printed Bridge Matrix for "distributed pyrotechnic"

The fixture experimented with was planar, but it is planned to print the bridge matrix on a transparent flexible backing. The entire sheet will then be loaded with a sheet of composition and formed to the walls of a cylindrical cavity in which the laser rod is placed. Such a fixture is presently being constructed (See Fig. 1).

C. Multiple Squib Fixture

The confining fixture shown in Photograph 1 used a single squib which attained a brightness approaching 5000° K. A fixture with four squibs in a row was then tested (see Photographs 4 and 5). Each of the individual squibs attained the same brightness as in the single squib fixture. The area between the squib hole was grooved to allow the gases to flow along a longitudinal channel from one squib cavity to the next. A brightness measurement made on the point between squibs showed it to be nearly as bright as the squib face. The typical squib face brightness would be 4800° K and the channel between squib was about 4300° K. The fixture represented an intermediate step between working with a matrix of single squibs and a continuous distribution of pyrotechnic composition.

D. Xenon Tube and Flash Bulb Brightness

To compare the relative brightness of pyrotechnics with other bright light sources, measurements were taken of xenon tubes and AG1 flash bulbs. Oscillograms 4 and 5 show the brightness-time curves for these items. Oscillogram 4 represents an FX100 longitudinal xenon

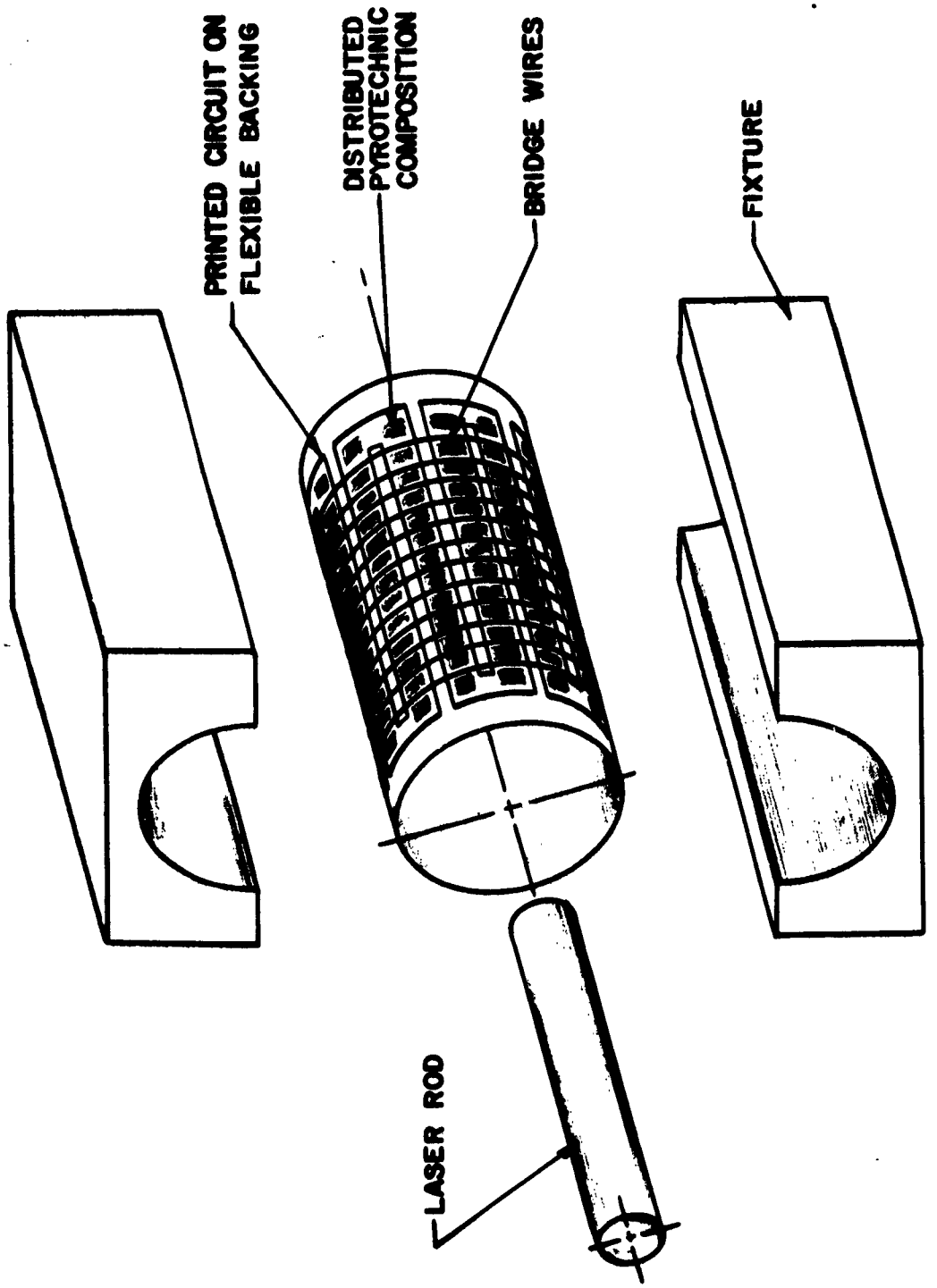
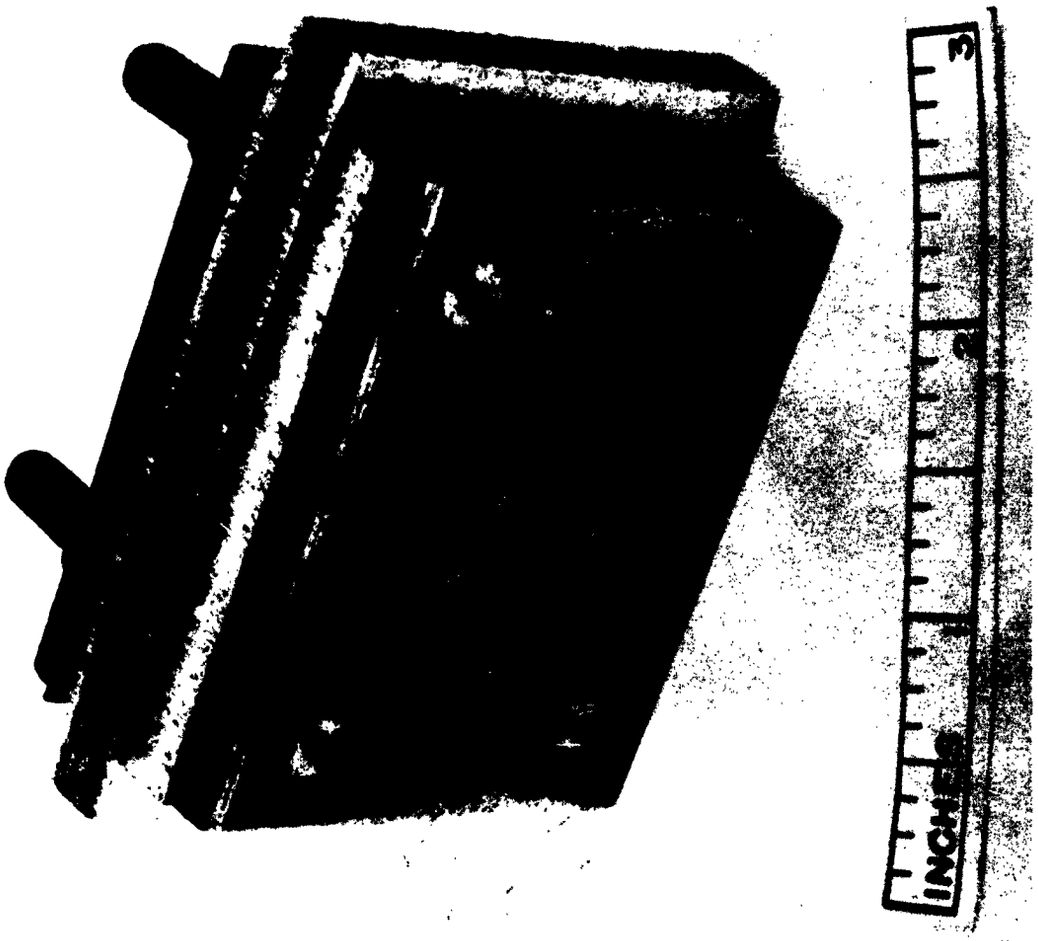
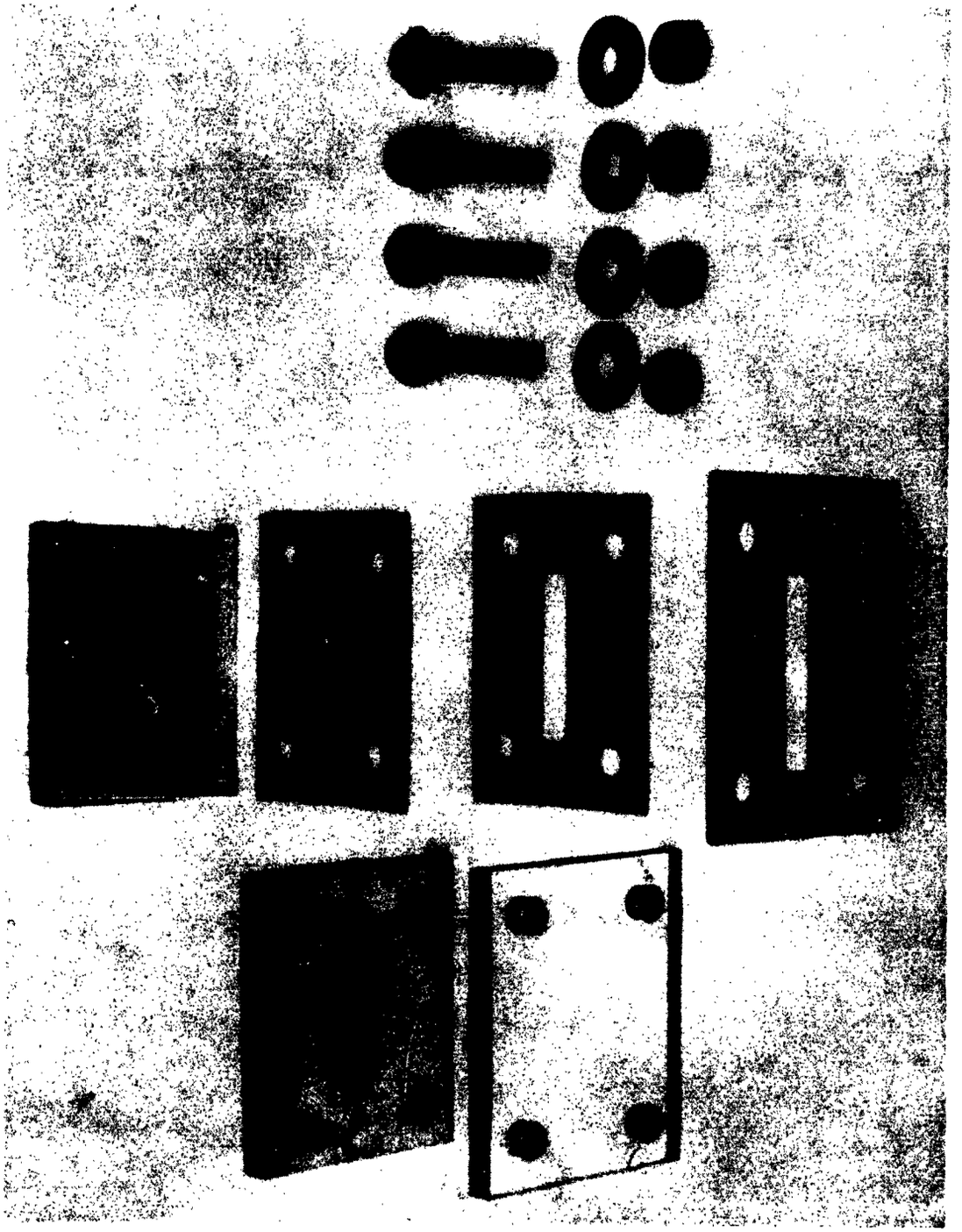


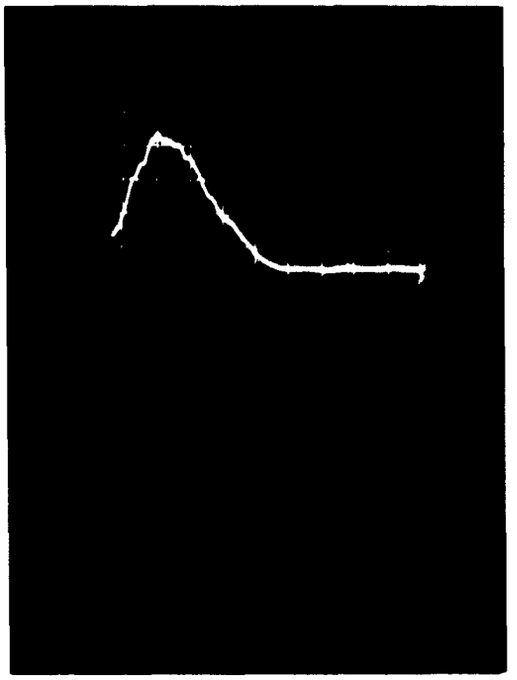
FIG. 1 - Proposed LASER Pump Fixture Utilizing Distributed Pyrotechnic on Printed Bridge Wire Matrix



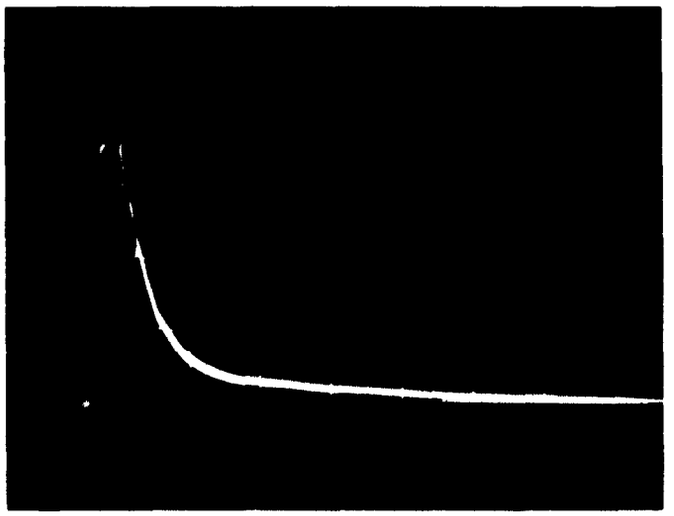
PHOTOGRAPH 4 - Multiple Squib Confinement Fixture



PHOTOGRAPH 5 - Multiple Squib Confinement Fixture
(Exploded View)



Oscillogram 5 - AG1 Flashbulb Brightness 5 msec/cm



Oscillogram 6 - M48 Detonator Shock Front in Conical Hole
2 msec/cm

tube pulsed with a 20 uf capacitor at 1400 volts. The peak brightness of this curve is about 8000° K. Oscillogram 5 shows the brightness-time curve for an AG1 flash bulb. The peak brightness is 3800° K. If 8000° K and 3800° K are converted into watts per cm^2 irradiated in the pumping band, they correspond to 5000 watts/cm^2 and 150 watts/cm^2. In this respect, the xenon tube at peak radiates about thirty-five times the flash bulb at peak. A relative scale of peak brightnesses in the band .485 microns to .660 microns is shown in Fig. 2, which relates watts/cm^2 to brightness temperature.

E. Metal-Oxygen System Brightness

The commercial photoflash bulb is an example of a metal-oxygen reaction. In the commercial flash bulb, however, the density of metallic fuel and oxygen is low for economy and safety reasons. It is conceivable that a heavy walled pressurized flash cartridge would have a higher brightness. The fixture shown in Photographs 6 and 7 has been designed. This fixture will be capable of withstanding high pressures during the reaction, and it can be loaded with zirconium and oxygen in a stoichiometric ratio so that the fuel-oxygen mixture is far more dense than in a commercial flash bulb. Results on the brightness of such a device are being taken and are not yet available at this writing.

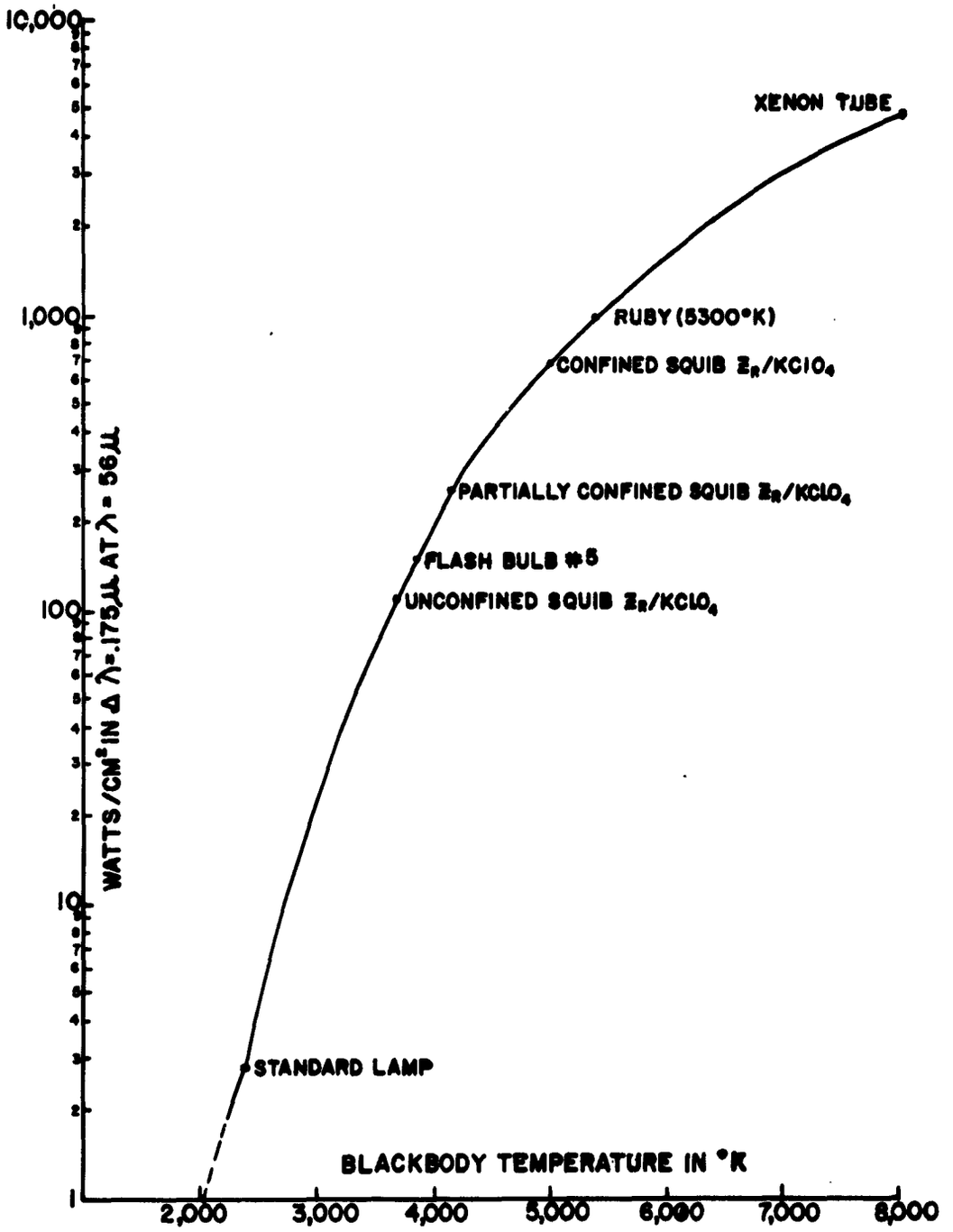


FIG. 2 - Typical Peak Brightness of Items at $\lambda = .56\ \mu$

PHOTOGRAPH 6 - Metal-Oxygen Brightness Fixture

PHOTOGRAPH 7 - Metal-Oxygen Brightness Fixture

(Exploded View)

F. Detonator Shock Front

The highest peak brightness that was measured is shown in Oscillogram 6. The peak brightness of this waveform was about 7000° K. It was produced by placing an M48 detonator in a conical shaped hole, as shown in Fig. 3. Without the benefit of the conical hole, a brightness of no greater than 4000° K is produced. The light rose to peak within one microsecond and the entire trace is less than five microseconds.

It is felt that in this case the detonator acted as a shock wave driver to the conical cavity. The high temperature observed would then be the shock front rather than the detonator reaction.

G. Pump Fixtures with $Zr/KClO_4$

The brightness measured on confined $Zr/KClO_4$ approaches 5000° K. Although this is low for ruby, which requires about 5300° K, it is more than sufficient to pump neodymium doped C_aWO_4 and possibly neodymium doped glass. The fixture shown in Photographs 8 and 9 was designed to attempt to pump a C_aWO_4 rod. The fixture contained six squibs in a row in order to illuminate the rod along its entire length. Confinement was obtained by having the flame flow between the fixture body and the lucite tube containing the rod. The venting on the fixture was adjusted by varying the spacing between the two halves. The fixture was first fired with a dummy C_aWO_4 rod and it was learned that a breakage problem exists. Although the squibs in this fixture are not brisant, the lucite tube did not

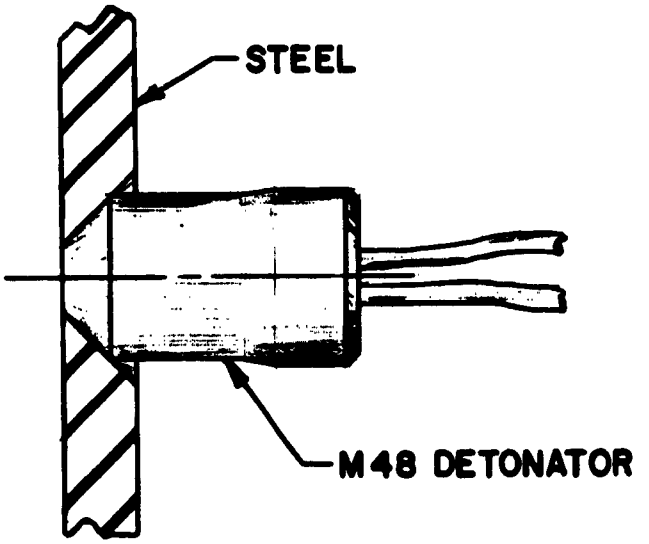
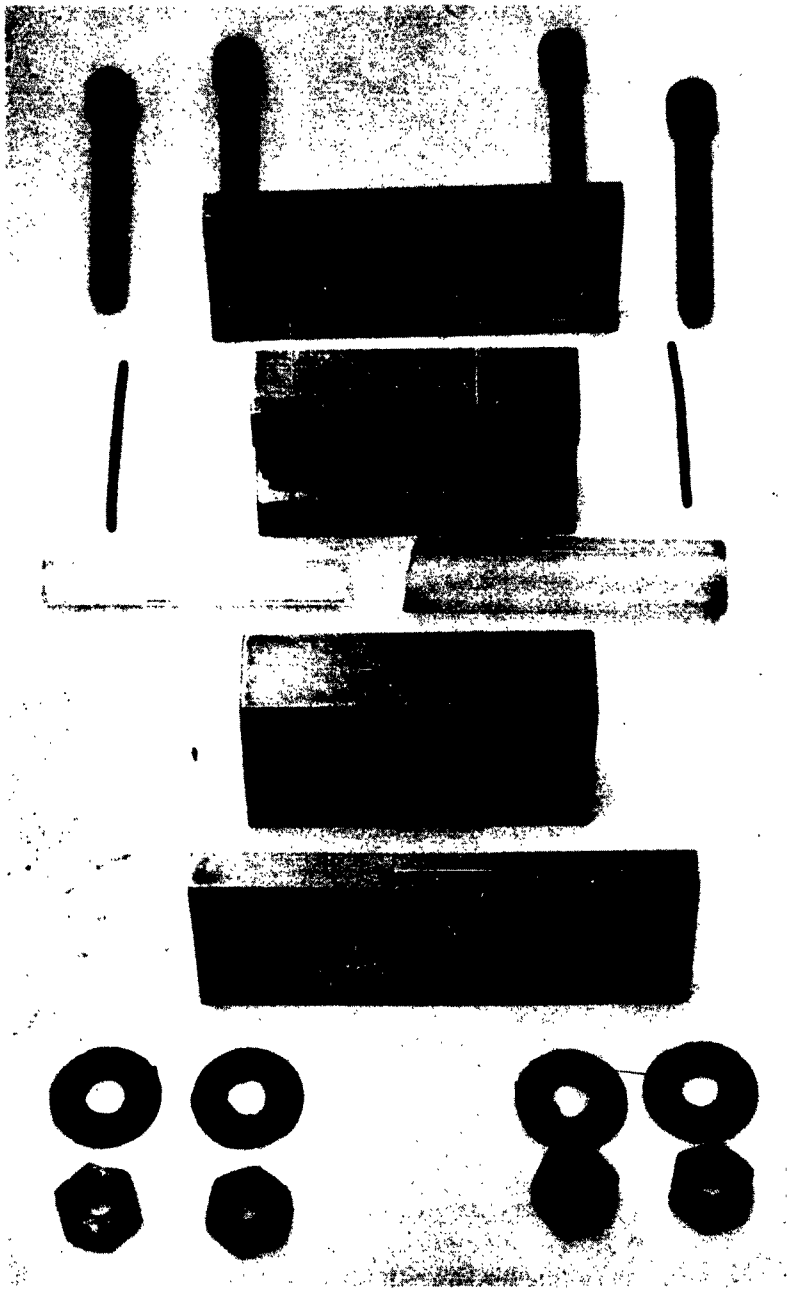


FIG. 3 - Arrangement for Producing Shock Front with M-48 Detonator

PHOTOGRAPH 8 - Squib-Laser Pumping Fixture



PHOTOGRAPH 9 - Squib-Laser Pumping Fixture (Exploded View)

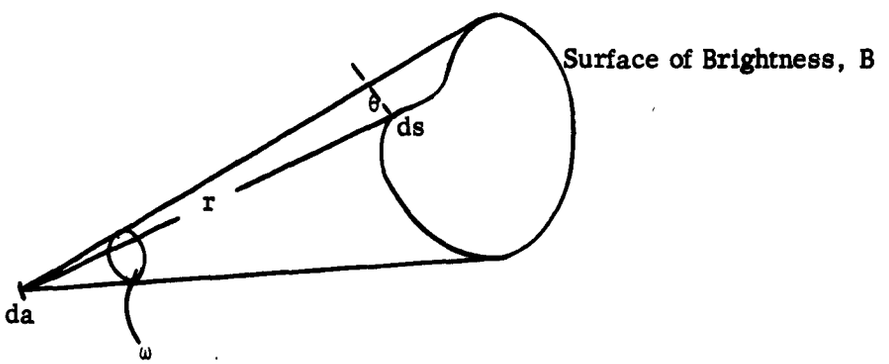
give enough support to the highly brittle $CaWO_4$. The crystal mounting technique is being improved upon before attempts are made to pump with this fixture.

III EXPERIMENTAL PROCEDURE

A. Brightness Measuring Apparatus

The illumination due to a radiating body of arbitrary shape is given by the expression

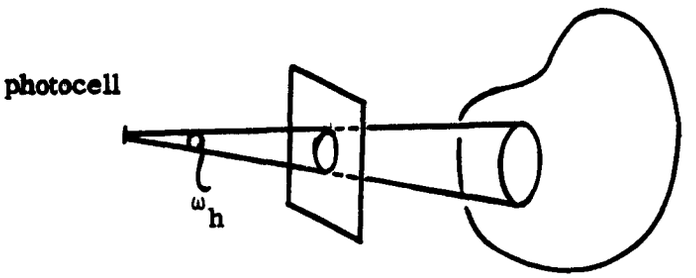
$$\frac{dw}{da} = I = \int_s \frac{B \cos \theta \, d s}{r^2}$$



where I is watts per square centimeter incident on a surface, and B is brightness of the source in watts per square centimeter per steradian. It can be seen that the integral function is really identical to the definition of the solid angle subtended by the projection of the object. The illumination can then be written as

$$I = B \omega$$

If the object is now placed behind a hole in such a manner that the object fills the hole relative to the field of view of the cell, the solid angle is now determined by the hole rather than by the dimensions of the object.

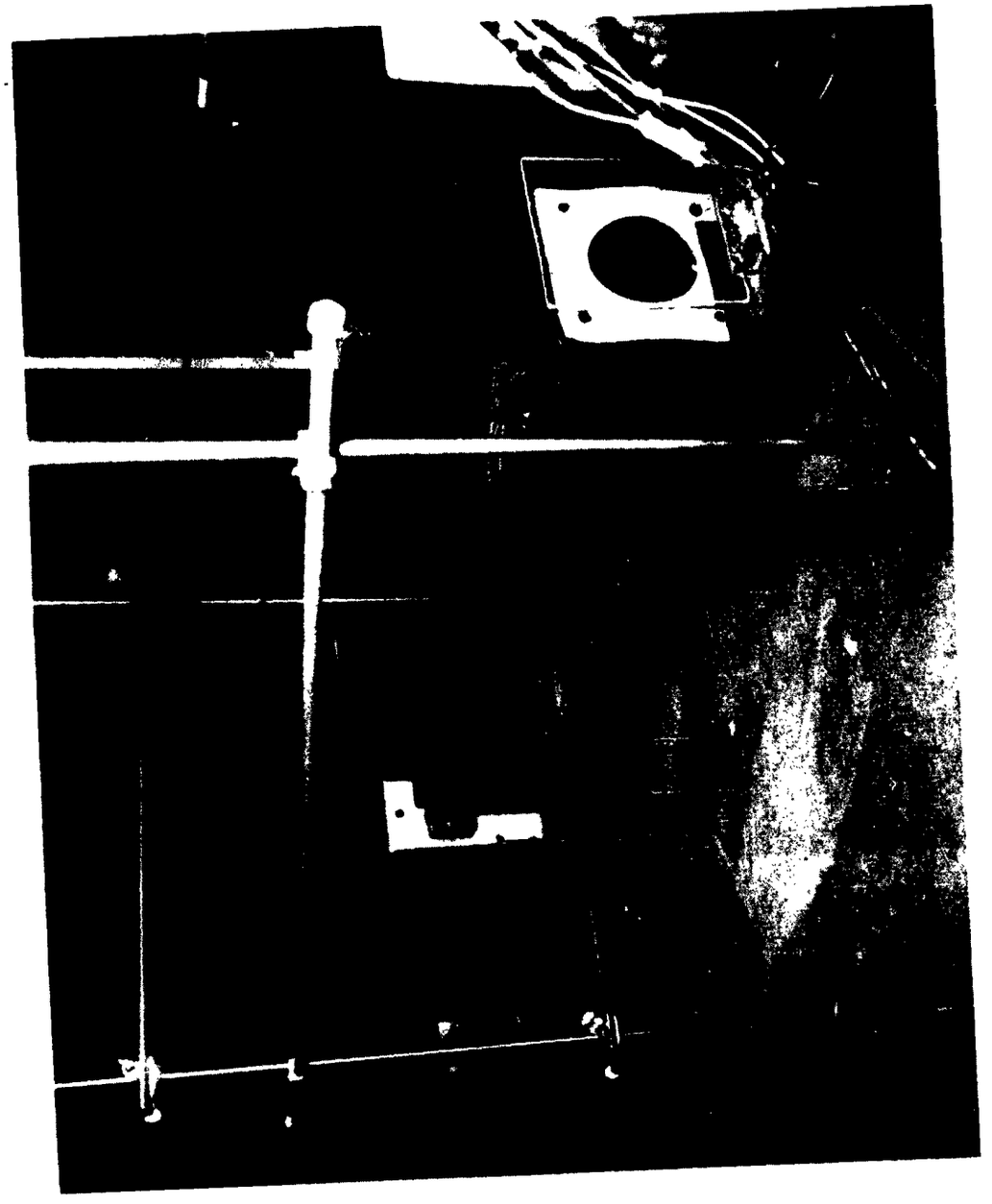


The illumination is then given by

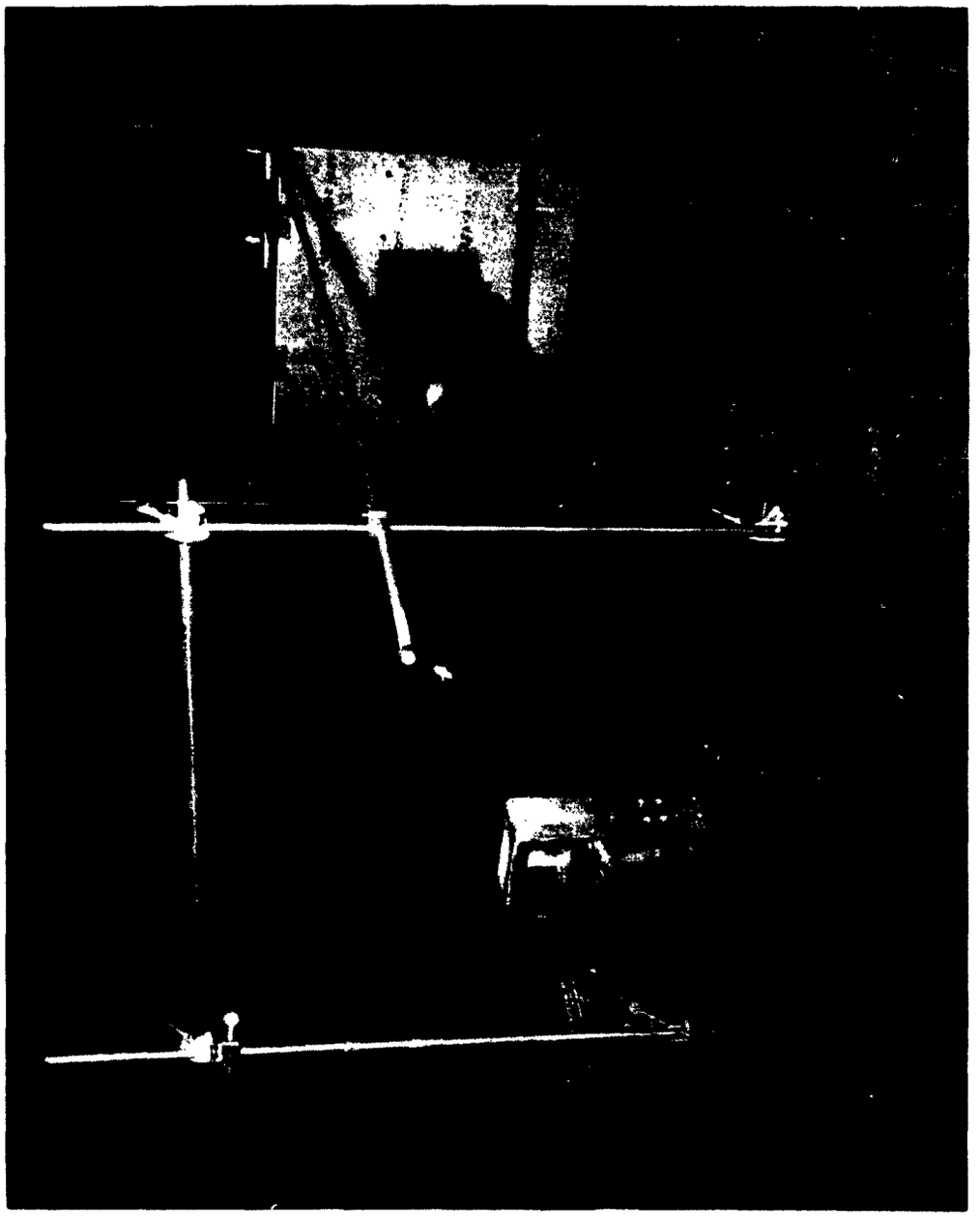
$$I = B\,\omega_h$$

and is independent of the distance of the object behind the hole. A photocell receiving this illumination would then give a response proportional only to the brightness of the object being measured.

Although a measurement of brightness could be taken directly in this simple manner, it is desirable in measuring the brightness of explosive compositions to utilize an optical arrangement, incorporating the same principles discussed above. This is due to the fact that particles and hot luminous gases can escape through the hole. The particles and debris can damage the photocell and the hot gases which would billow out, would contribute an illumination of its own, confusing the brightness measurement. A bench apparatus was designed as shown in Photographs 10 and 11. The lens forms a real image with some magnification, and the photocell then receives



PHOTOGRAPH 10 - Brightness Bench



PHOTOGRAPH 11 - Brightness Bench

radiation from the image. The image acts as a source of light of brightness B'. It can be shown that for an image formed on the axis of the lens (neglecting losses), the image brightness B' is identical to the object brightness B, and is independent of the magnification, m. The image is observed through a small hole in the image screen. In order that the photocell response be proportional to the brightness of the object, two criteria must be met.

1. The lens must be large enough to subtend the solid angle determined by the photocell and the image hole, ω'.

2. The image must fill the image hole relative to the photocell for the same reasons as discussed above. When these conditions are met,

$$I = B' \omega' = B \omega' \quad \text{(since } B = B'\text{)}$$

Analysis of Optics

As shown in Figure 4, the lens system is initially set up so that any point in the plane of the object screen at p_o will be in focus on the image screen at q_o. These planes are the initial reference planes. Assume that an object of lateral dimension h is placed δ centimeters behind the plate. Its image will have lateral dimensions h' and will occur at x as shown in the figure. The image hole has a diameter s. Let d be the distance from the image screen to the photocell. If we assume that condition (1) has been met, we wish to determine how far an object of known lateral dimensions can be placed behind the object hole and still meet condition (2).

The dimension of the image will be given by

(1)
$$h' = \left(\frac{f}{p_o + \delta - f} \right) h$$

where f is the focal length of the lens.

The image will be formed at

(2)
$$x = \frac{f^2 \delta}{(p_o - f)(p_o + \delta - f)}$$

The minimum condition that h' fill the hole s, is given by

(3)

$$h' = s\left(1 + \frac{x}{d}\right)$$

In order to meet this minimum condition, substitute equations 1 and 2 into equation 3. It is then determined that

(4)

$$\frac{fh}{s} = (p_o + \delta - f) + \frac{f^2 \delta}{d(p_o - f)}$$

Let m_o be the system magnification for the reference planes; that is, an object placed at q_o ($\delta = o$). We will have a magnification m_o of its image.

$$m_o = \frac{f}{p_o - f}$$

Using this relation, equation 4 can then be written

(5)

$$h = s\left[\frac{1}{m_o} + \delta\left(\frac{1}{f} + \frac{m_o}{d}\right)\right]$$

The distance behind the screen δ , is now known in terms of the lateral dimensions of the object. For δ less than that shown in equation 5, the condition 2 will be met. If the object is placed as some δ greater than this, condition 2 will not be met and the photocell response will not be

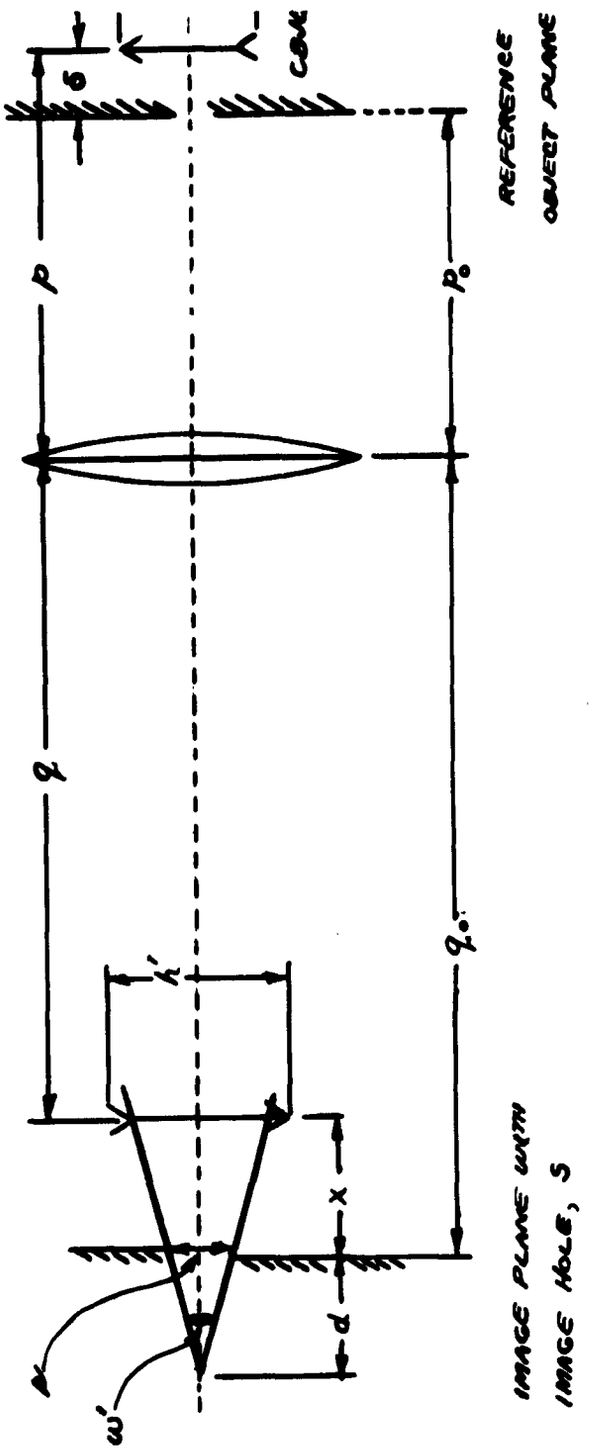
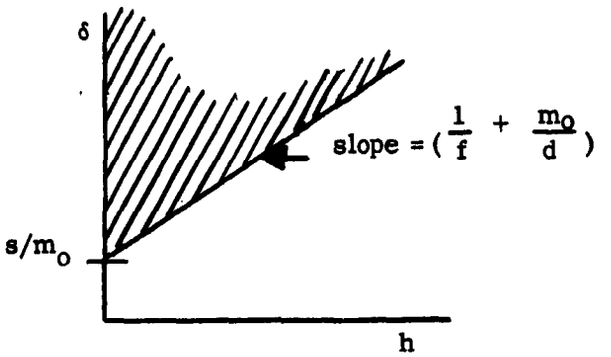


FIG. 4 - Brightness Bench Optics Schematic

proportional to the brightness of the object. A plot of this information is shown below.



An object at δ will meet the minimum requirements if (δ, h) falls in the shaded area. To calibrate the system, a standard ribbon filament lamp is placed behind the object hole in such a manner that all criteria are met. The lamp has a known brightness temperature of 2400° Kelvin. Since it is known what band of wave lengths the photocell is responsive to, Planck's Law can be utilized to calculate the radiant energy in watts per square centimeter emitted by the lamp. Note that the radiant energy in watts per square centimeter emitted by any Lambert radiator is simply π B where B is in watts per square centimeter per steradian. Since the photocell response is directly proportional to B, the system can be calibrated in terms of output volts versus watts per square centimeter of source brightness in a known band. Neutral density filters are utilized to keep the photocell response to an unknown object in its linear and calibrated range. The brightness temperature of an object (in the band in which we are interested) can then be computed by utilizing Planck's Law.

B. Brightness Measurements

The basic requirement for pumping is the watts per square centimeter incident on the crystal in the absorption band of the laser medium. Threshold pumping can be defined as that number of incident photons per unit area per unit time of a particular energy that will produce a 50% population inversion of the active material. Population inversion means that 50% of the absorbing atoms are excited and raised to the pumping energy level.

In order to evaluate transient sources as pumps, the optical apparatus described in the previous section was used. The relation between J_λ (watts per square centimeter per millimicron) and temperature is for a blackbody,

$$J_\lambda = \frac{\frac{C_1}{\lambda^5}}{e^{\frac{C_2}{\lambda T}} - 1}$$ Planck's Law

A typical calibration of the optics by means of a 2400° K standard lamp produced a signal output (J_λ) of 967 millivolts.

$$J_\lambda = C_1 \lambda^{-5} \left(e^{\frac{C_2}{\lambda T}} - 1 \right)^{-1}$$

$$C_1 = J_\lambda \left(e^{\frac{C_2}{\lambda T}} - 1 \right) \lambda^5$$

$\lambda = .53\ \mu$

$T = 2400^{\circ}$ K

$C_2 = 14320$ (fundamental constant)

$C_1 = 3{,}114{,}000$

$J\lambda = 967$ MV

This is the constant for the experimental arrangement.

To determine the brightness temperature for the unknown sources initiated in the object plane of the optical bench, Planck's Law was again used in the form.

$$T = \frac{C_2}{\lambda \ln \left(\frac{C_1}{J_{\lambda_i} \lambda^5} + 1 \right)}$$

when $J_{\lambda i}$ is the signal output of the item.

It should be noted at this point that the above calculation is not exactly correct and is only valid for measuring the brightness temperature of an item at a specific wavelength when viewing it through a narrow band filter. An exact measurement is only possible when the spectral distribution of the item is known in conjunction with the photocell-filter wavelength response function. Experience with typical pyrotechnic spectral

distribution functions, however, indicates that the above method is accurate enough to serve its purpose. The following analysis should suffice:

The exact brightness temperature of an item is quoted from the following definition:

(1) $$\int_{\lambda_1}^{\lambda_2} W(\lambda,T)d\lambda = \int_{\lambda_1}^{\lambda_2} J(\lambda,T_B)d\lambda$$

$W(\lambda,T)$ = Item spectral distribution

$\lambda_2-\lambda_1$ = Spectral band of interest

$J(\lambda,T)$ = Blackbody spectral distribution

T_B = Brightness temperature

T = Item true temperature

The signal measured on the scope for an item is really proportional to

(2) $$\int_{\lambda_1}^{\lambda_2} f(\lambda)W(\lambda,T)d\lambda$$

Where $f(\lambda)$ = spectral response function of "filter-photocell"

Where an item signal is compared with the calibration signal, the following is true:

(3) $$\int_{\lambda_1}^{\lambda_2} f(\lambda)W(\lambda,T)d\lambda = \int_{\lambda_1}^{\lambda_2} f(\lambda)J(\lambda,T_X)d\lambda$$

Where T_X is the lamp temperature necessary to produce the same signal as the item.

The method used to calculate brightness temperature is valid if the following things are true:

(a) The item has a graybody distribution over the band of interest

$$W(\lambda) = KJ(\lambda) \qquad \lambda_1 < \lambda < \lambda_2$$

(b) $\lambda_2 - \lambda_1$ is small enough so that $f(\lambda)$ is assumed constant over the range.

C. Photometers

In determining the effectiveness of sources for pumping, the ruby was the first medium considered. Since the ruby had a strong absorption band at .4 microns, a S-4 surface was chosen as the cell. The S-4 surface also peaks at .4 microns (see Fig. 5). This photoemissive cell was mounted in a light tight housing along with a cathod follower and associated electronics. The cell was maintained within its linear range by the use of neutral wire screen filters.

The rise time of the cathode follower excluding the photocell was determined experimentally by the use of signal generator. A sine wave applied to the input of the cathode follower and cables was increased in frequency until the output dropped off to the .707 point.

$$f = \frac{1}{2\pi RC}$$

This approximation yields an RC of .012 microseconds. The rise time (10% - 90% points) is 2.2 x .012 = .026 microseconds for the circuit excluding the photocell.

When it became evident that the neodymium materials would have a much lower threshold, a different cell and filter combination was devised having a window from .48 to .66 microns with a peak transmission at .56. This peak point represents the strongest absorption band for glass and calcium tungstate doped neodymium. This photometer head consisted

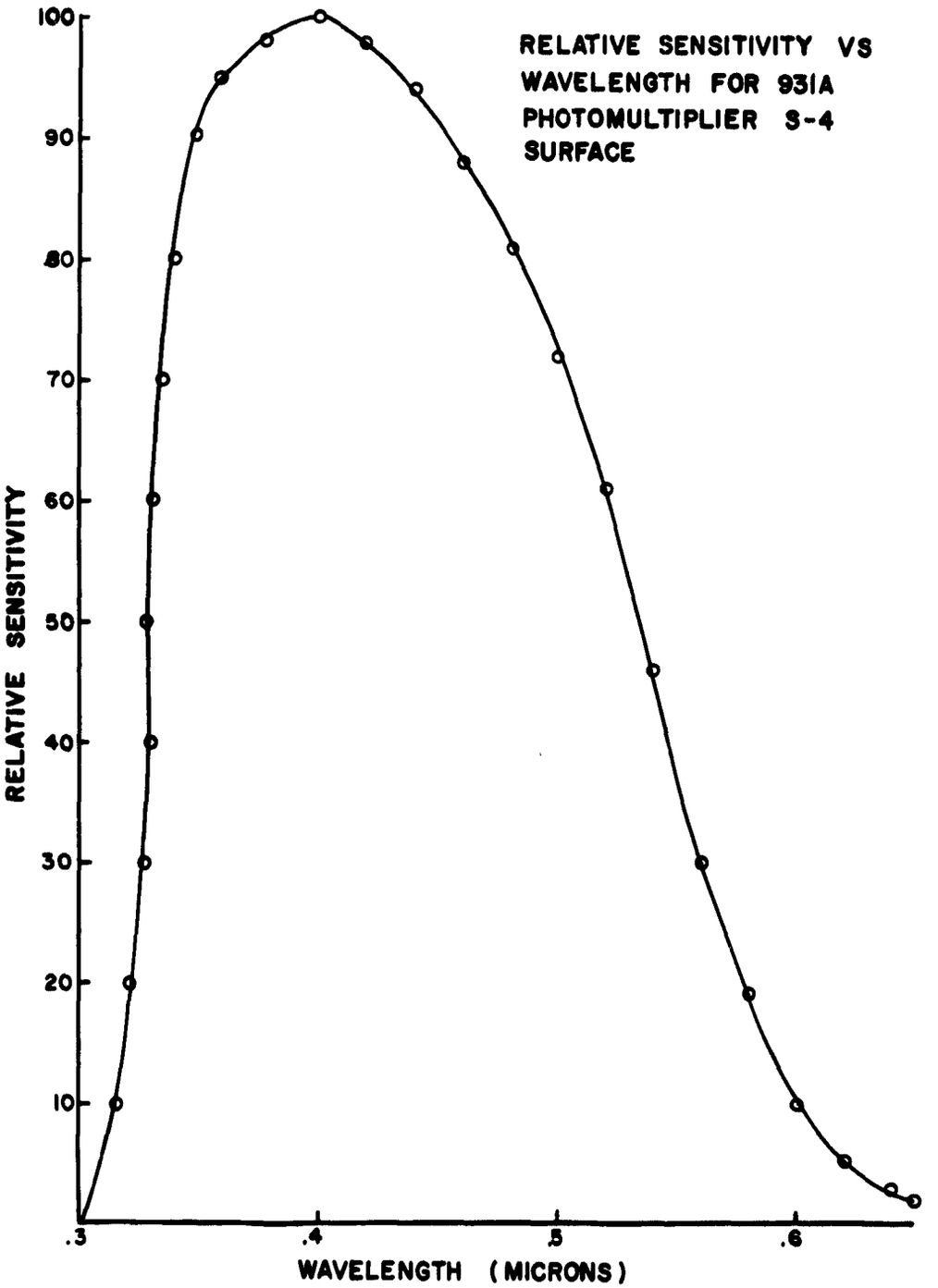


FIG 5 - S-4 Wavelength Response

of a small photovoltaic type cell and colored filters. Due to the small size of the sensitive surface, neutral density rattan type filters were used (rather than wire screen) for keeping the cell within its linear range. Again a cathode follower was used to couple the 1000 ohm impedance of the cell to the cables and connectors of the oscilloscope. This photocell filter response curve is shown in Fig. 6. All brightness data reported here are for the Philco L4413 cell with associated filters, the response of which peaks approximately at the neodymium absorption band.

To observe the laser output, it was necessary to construct a fast response photometer. For this purpose a photomultiplier was used and again the load resistance 100 ohms was matched to cables and connectors. The time response of this arrangement was checked by a commercial light source having manufacturers' guarantees of a rise time of a few nanoseconds. The results of observing this fast rise light source showed a rise time to peak of approximately 10 nanoseconds. Some of the traces of lasing near threshold are shown in Oscillograms 7 and 8.

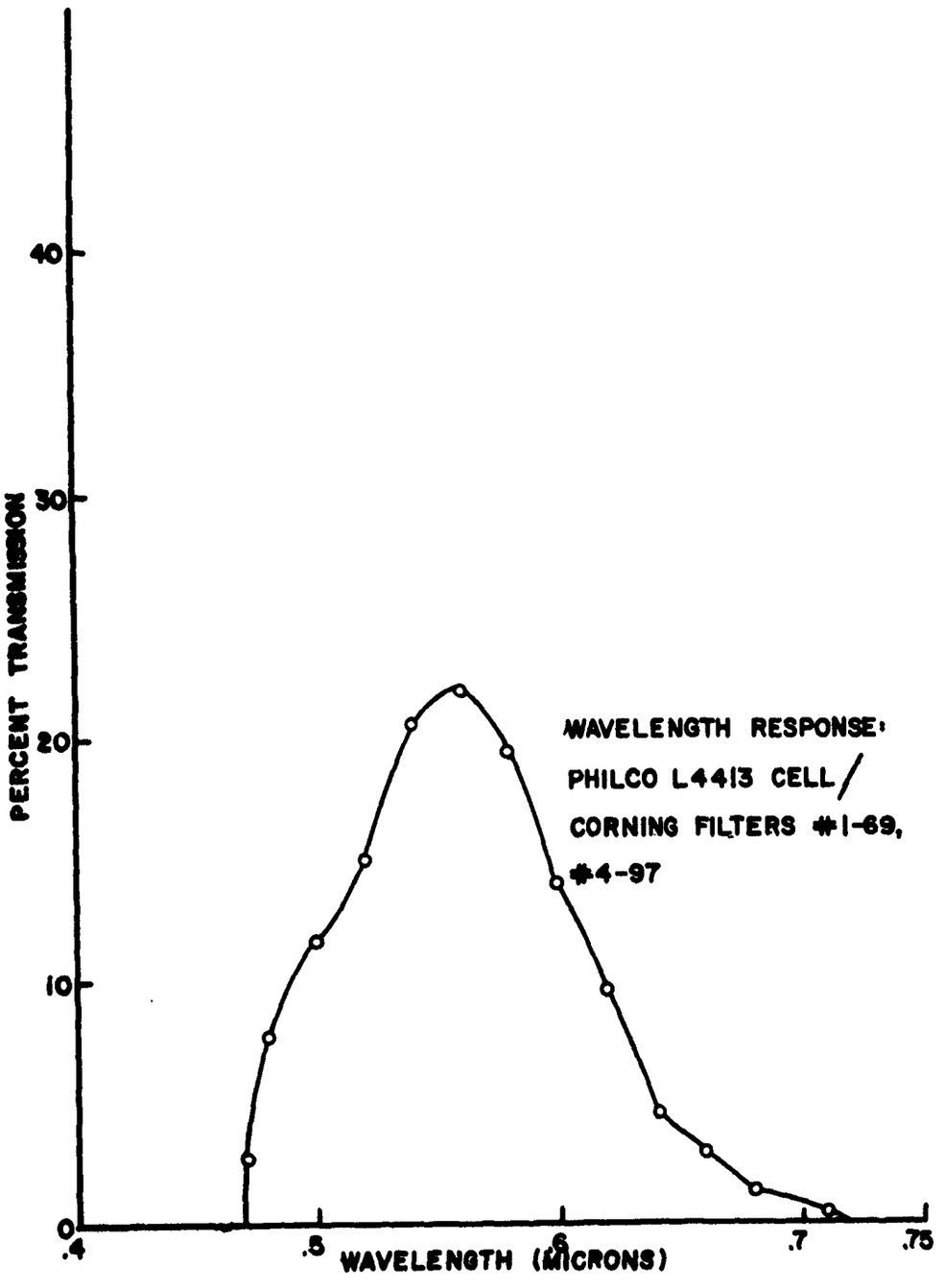
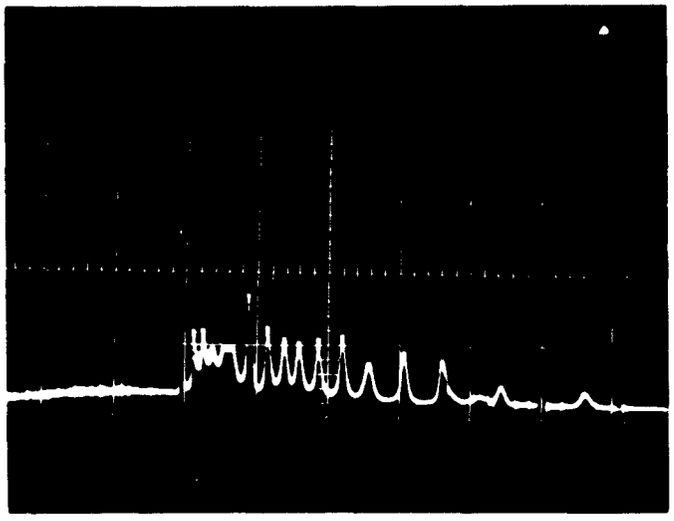
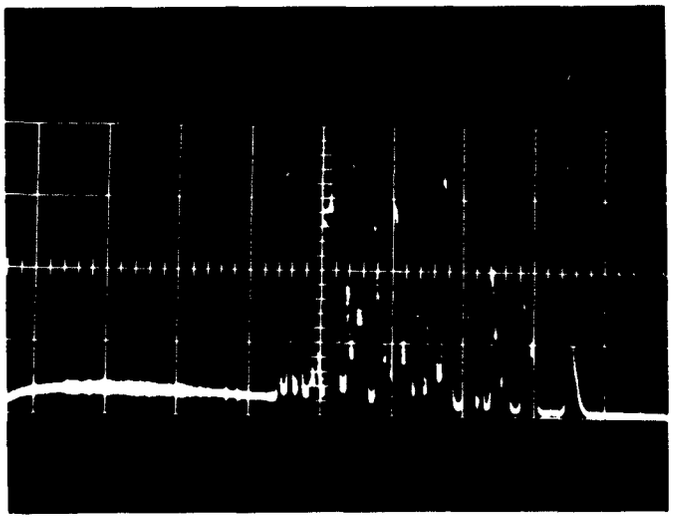


FIG. 6 - Philco Cell Wavelength Response (With Filters)



Oscillogram 7 - Nd - $CAWO_4$ Lasing at 25 joules



Oscillogram 8 - Nd-$CAWO_4$ Lasing at 65 joules

IV DISCUSSION OF RESULTS

A. One of the test vehicles chosen for convenience and small size was a squib body. This is a small cylinder about 1/4" long, and 3/16" inside diameter. It has a 1 ohm bridge wire which is heated by electrical current to initiate the composition. In the multiple squib fixtures, as described in Section II C where multiple squibs were tested, it was found that a simultaneity of initiation problem existed. When six such items were fired in parallel from a common source, the individual light output peaks were spread out over a period of about 1 1/2 to 2 milliseconds. This is not desirable for pumping rods with a mean fluorescent life time around 200 to 300 microseconds. It would be more suitable for the ruby as this material has a 3 millisecond mean fluorescent life time. This does not mean that this fixture and squib arrangement could not pump a calcium tungstate rod; but simply that optimum use is not being made of the source. It is therefore necessary to consider simultaneity in any source designed specifically for pumping these materials, such as the "distributed pyrotechnic" already discussed. This design incorporates a large number of ignition elements to provide for a more simultaneous initiation of the surface. Other means of improving this have been considered, such as using a primer composition on the bridge wires.

It is seen from the results that confinement increased the brightness temperature from about 3800° Kelvin to 4900° Kelvin, with

the highest brightness being obtained with a particular fixture where the gases were permitted to build up and rupture a rubber gasket in the area of the lucite window, where the bright surface was being observed. Further increasing confinement by the use of the fixture shown in Photograph 1 (left) brought the temperature back down to 4000° Kelvin. Examination of both of the fixtures showed that the one containing the ruptured device maintained a clear window after firing (lucite sheet), while the more highly confined arrangement either destroyed the window completely or completely blackened it. It is felt that a higher temperature may have been attained in the more highly confined fixture but that the bright part of the reaction was obscured by the gases, whereas in the ruptured apparatus the gases were allowed to escape by the window and the brighter part of the reaction could be observed. Providing a means of looking into such a reaction has long been a problem and it is expected to be one of significant areas, requiring investigation in the development of a laser source.

B. Reaction Temperature Considerations

The temperature limits which may be attained in a pyrotechnic composition will depend on the pressure of the system. At one atmosphere of pressure the maximum temperatures are largely limited by the boiling points of the oxides. Calculations are being made to determine the effect of pressure on temperature for several oxides. In the case of aluminum oxides temperature dependency plots of the log of the equilibrium pressure

vs. 1/T were made. From this plot, the heat of vaporization was calculated to be 128 K cal/mole. The equation of the curve was determined to be:

$$\log \text{Peg (mm)} = \frac{27.8 \times 10^3}{T} + 11.5 \qquad (1)$$

Solving for T gives:

$$T = \frac{27.8 \times 10^3}{10.2 - \log \text{Peg (mm)}} \qquad (2)$$

It should be pointed out that in calculating the temperature at high pressure, the approximation was made that the heat of vaporization remains constant and that the vapor pressure data are correct. The constants in this equation were corrected so that the boiling point corresponds to the accepted value of the boiling point, 3800°K. Since there is some variation in these values in the literature, the calculations depend on the source of the data. However, it is of value to obtain an estimate of the pressure effect. The following table shows the variation in temperature with pressure pased on equation 2.

P (atm)	Temp °K
13.2	4,480
132.	5,340
1,320.	6,620
13,200.	8,700
132,000.	12,670

There are other oxides which have substantially higher boiling points than Al_2O_3 such as the oxides of Zr and Th and for which calculations

are being made at this time.

In the case of the reaction between aluminum and oxygen, it is estimated that the heat of reaction is sufficient to raise the temperature of the aluminum oxide under the proper conditions of confinement to approximately 10,000°K. This, however, neglects the dissociation of aluminum oxide to AlO and O_2 which should somewhat lower this temperature. In the case of the reaction of aluminum and potassium perchlorate, the maximum temperature will be somewhat lower than that of the reaction of aluminum and oxygen because of the formation of KCl. The importance of the high temperature dissociation reactions of the metal oxides and the lack of high temperature data clearly indicates the need for basic research in this area. It is also believed that the emissivity under conditions of high pressure should increase; thereby raising the pumping efficiency of the reaction. In the above discussion, equilibrium conditions have been assumed that any one instant it is possible for higher temperatures to exist in the reaction zone.

Although it is known that the amount of discreet emission observed from a high temperature reaction decreases with the concentration and pressure in the reaction zone, it has not been established whether the amounts of materials and the instantaneous conditions will be a cause for only continuous emission in the proposed system. Accordingly, the addition of impurities such as chromium, barium, strontium, etc. will be investigated.

The following parameters which can also markedly affect the reactions were considered:

a. Weight of item

b. Particle size of ingredients

c. Type of initiator

d. Weight of initiator

e. Location of initiator

f. Compaction

g. Binder

h. Humidity

V CONCLUSIONS AND RECOMMENDATIONS

A. Pyrotechnic compositions consisting of two basic ingredients - fuels and oxidizers - were tested in various combinations. The compositions experimented with are listed in Chart No. 1. Combinations of pyrotechnic ingredients and high explosives were also examined and high explosives in various configurations were tested. These brightness tests were also conducted with various means of containing and confining the materials. $Zr/KClO_4$ emerged as the brightest emitter, and the brightness was enhanced by the use of a fixture shown in Photographs No. 1 and 2 (center). Also, the ingredients were varied from stoichiometric to fuel rich combinations, with the stoichiometric ratio giving the constantly highest output on the brightness bench. The temperature arrived at with this combination was about 4900^{o} Kelvin. Fixtures producing even higher degrees of confinement, and consequently higher explosive forces, were also tested but a lower brightness temperature was obtained than with the optimum fixture. It is suspected that the reason for this is the lack of a proper window for observing the brightness portion of the reaction. This point requires further investigation.

It is also suspected that a higher temperature than 4900^{o} Kelvin is being produced. Some theoretical work has been done that shows even higher temperatures can be produced with a fuel such as thorium. Thorium oxide which would be produced, has an even higher stability than the oxides tested. The use of thorium along with higher pressures are expected to produce higher

temperatures, and in turn a greatly increased light density. Finding an optimum way of looking into these burning reactions is also a formidable problem and requires study and experimentation, and is another phase presently being given consideration. Thorium has been obtained and a means of handling and loading this material with oxidants is now in progress.

It is also felt necessary to refine the brightness measuring techniques to a higher degree by looking at more selective bands in the spectrum. This is also expected to enhance the brightness readings as there will be some lines associated with these reactions. This will involve a considerable amount of work. A combination of interference filters and cells will be selected and calibrated to observe the brightness in specific spectral regions.

New reactions must be investigated to search for brightnesses approaching that of the Xenon tube. A weapon system designed about such a laser pump would be much more practical than one utilizing a laser pump. This will be due to the elimination of power supplies and high voltage initiation equipment. It is difficult to predict theoretically the maximum attainable brightness temperature that these new exotic fuels will provide since the information in the literature is mainly restricted to ambient pressures. Therefore, extrapolation of the curves to many atmospheres becomes questionable.

B. Recommended Future Program

A future program is dictated by the following considerations. Burning

chemical sources do not have the inherent brightness properties of gas discharges. The highest brightness temperatures measured with pyrotechnics so far have been about 5000° Kelvin, whereas the xenon gas discharges are about 8000° Kelvin. The brightnesses that are obtained with pyrotechnics, however, are sufficient for pumping some laser materials and nearly sufficient for pumping ruby. The advantages of the pyrotechnic is that it can be distributed into a uniform flame area which burns for a relatively long time. Because of these advantages, what is lost in brightness of a pyrotechnic must be gained by ease of better coupling. With this background in mind, the following program is planned:

1. The distribution of flame areas formed by squibs or distributed pyrotechnics will be investigated. The desirable end result is to attain a continuous cylindrical flame distribution completely surrounding the laser rod. With such a distribution, it is possible to approach perfect optical coupling from the flame to the crystal.

2. Crystal mounting must be improved in order to eliminate breakage of the laser due to small flexures and vibrations in the fixture. This will be attempted by trying to mechanically isolate the crystal from the fixture walls. A proposed scheme is to "float" the crystal in a gelatinous potting compound inside of a clear plastic tube (lucite or Lexan) It has been considered to run a spiral groove along the outside of the tubing to direct the flame around the entire outside of the cylinder. Inexpensive dummy

crystals of calcium tungstate will be secured to insert into any fixture prior to attempting lasing.

3. Consideration will be given to the temperatures that will result in a pyrotechnic flame cavity. Measurements can be made of the temperatures reached inside such a cavity. If the temperature problem is severe, consideration will be given to keeping the laser cool by surrounding it with media that absorb infrared, and thermally insulate the crystal while passing the pump frequencies.

4. Various pyrotechnic compositions have always been in squib bodies. This system has been easiest to work with, but in order to get best optical coupling, it is possible that working with individual squibs is a limitation. New loading techniques in which a composition is pressed into a continuous cylindrical sheet will be investigated. A preliminary experiment on such a composition sheet (a planar sheet) has indicated feasibility. A problem area that arises when working with distributed composition or many squibs is that of simultaneity of light from various areas of the composition, or from various squibs. This is a serious problem when working with laser crystals with relaxation times that are short. With no simultaneity a laser crystal is not pumped in all places at the same time. To make best use of the available light, it is necessary that simultaneity of the flame areas be small compared to the crystal relaxation time.

5. Most work to date has been done with the composition of Zirconium-Potassium-Perchlorate. This composition has been easy to handle and high brightness (approaching 5000° Kelvin) has been attained. The Chemical Department is presently working on a new composition utilizing thorium. It is hoped that the brightness temperature can be increased by a few hundred degrees with this composition. When the new squibs are available, a brightness temperature program will be run on the squibs.

A search will continue for more exotic higher temperature reactions. Potential high brightness chemical reactions might be as follows:

a. gaseous cyanogen - gaseous oxygen

b. gaseous cyanogen - gaseous nitrogen tetraoxide

c. liquid cyanogen - liquid nitrogen tetraoxide

6. Pyrotechnic compositions because of their spectral distribution will obviously be better able to pump certain crystals than others. It is proposed that a program be set up to investigate the spectral distributions on these compositions, to then measure the brightness time curve in a promising band and to then consider that composition as a potential pump for certain lasing material.

A cost estimate for a one year continued program is as follows:

	Time on Program
Physicist	Full
Electronic Design & Data Acquisition	Full
Electronic Technician	1/4
Ammunition Handler	3/4
Chemist	2/3
Mechanical Engineer	1/2
Machinist	1/2
(Approximately $95,000)	4 2/3 man years

OTHER COSTS

Item	Segment	Estimated Cost
Fabrication of printed circuits	Industrial Division	$ 5,000
Materials, rods, etc.	Industry	6,000
Cladding Materials	Plastic Lab or Private Industry	1,000
Metal Parts		1,500
Photocells and Filters	Private Industry	3,000
Travel		5,000
Spectroscopy Studies		7,000
	TOTAL	$28,500
	GRAND TOTAL	$123,500

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